Sensory feedback signal derivation from afferent neurons

Contract No.: **NIH-NINDS-NO1-NS-3-2380**

QUARTERLY PROGRESS REPORT #12

for the period

1 Sept. 1995 - 30 Nov. 1995

Principal Investigator:	J.A. Hoffer, PhD
Co-investigators:	K. Strange, BASc Y. Chen, PhD P. Christensen, BASc D. Crouch, BSc (Hon) M. Hansen, BScEE K. Kallesøe, MScEE C. Kendall, RVT
Origin:	School of Kinesiology Faculty of Applied Sciences Simon Fraser University Burnaby, British Columbia V5A 1S6, Canada
Subcontractor:	D. Popovic, PhD University of Miami, Miami, Florida, USA

Date of submission of this report: 18 Dec. 1995

Table of Contents

I. Summary of the Overall Project

In this study we are exploring the feasibility of extracting 1) cutaneous sensory information about fingertip contact and slip, and 2) proprioceptive sensory information about wrist or finger position. We use implanted nerve cuff electrodes to record peripheral nerve activity in animal models.

Our overall **objectives** for the 3-year duration of this contract are as follows:

1. Investigate, in cadaver material, implantation sites for nerve cuff electrodes from which cutaneous and proprioceptive information relevant to the human fingers, hand and forearm could be recorded.
2. Select a suitable animal preparation in which human nerve dimensions and electrode placement sites can be modeled and tested, with eventual human prosthetic applications in mind.
3. Fabricate nerve cuff electrodes suitable for these purposes, and subcontract the fabrication of nerve cuff electrodes of an alternate design.
4. Investigate the extraction of information about contact and slip from chronically recorded nerve activity using these animal models and electrodes. Specifically,
    a. Devise recording, processing and detection methods to detect contact and slip from recorded neural activity in a restrained animal;
    b. Modify these methods as needed to function in an unrestrained animal and in the presence of functional electrical stimulation (FES);
    c. Record activity for at least 6 months and track changes in neural responses over this time.
5. Supply material for histopathological examination from cuffed nerves and contralateral controls, from chronically implanted animals.
6. Investigate the possibility of extracting information about muscle force and limb position from chronically recorded neural activity.
7. Cooperate with other investigators of the Neural Prosthesis Program by collaboration and sharing of experimental findings.

II. Summary of Progress in the Twelfth Quarter

During the twelfth quarter, we made significant progress in investigating the use of nerve cuff signals in closed-loop control of functional electrical stimulation. Through computer simulations we demonstrated that cutaneous neural signals can be used to predict the timing of muscle activity during walking, and the results of simulations for a variety of walking conditions and subjects showed that the approach was both reliable and robust. This work was presented at the 26th NIH meeting in Bethesda, MA, at the IEEE Systems, Man, and Cybernetics meeting in Vancouver, B.C., and at the Neuroscience meeting in San Diego, CA. We have also made progress in redesigning the forelimb task hardware and software, and we are preparing for further implants and recordings of sensory neural activity during voluntary tasks.

As a consequence of delays that occurred in 1994 because of laboratory renovations and personnel transitions, we requested and were granted an extension of the time to completion of this contract work until March 30, 1996, at no additional cost.

III. Details of Progress in the Twelfth Quarter

A. Chronic Recordings from Year Three Implants

In Year Three we have implanted two cats to date. The first cat (NIH 15) was implanted with a nerve cuff electrode on the distal Median nerve, a nerve patch electrode on the Superficial Radial nerve, and miniature hybrid cuff/patch electrodes on the nerve branches to Extensor Digitorum Lateralis and Flexor Digitorum Profundus (5th head). Details of these devices were given in Progress Report # 11. The proximal branches of the Median and Radial nerves were also instrumented with stimulating nerve cuff electrodes in order to monitor the Compound Action Potentials (CAPs), and EMG patch electrodes on the Palmaris Longus (PalL), Flexor Digitorum Profundus (FDP), Extensor Digitorum Lateralis (EDL), and Extensor Digitorum Communis (EDC).

Table 1 provides a summary of the status of the instrumented nerves in NIH 15 up to the end of November, 1995. The FDP nerve CAP has experienced a progressive, gradual decline throughout the implant period, although the ENG signal still shows distinct and appropriate modulations of activity during voluntary tasks such as walking on the treadmill (see Progress Report #11).

Table 1: Status of subject NIH 15, Nov. 30, day 175.

Subject	Total Days Implanted	Median CAP Amplitude (% day 0)	Radial CAP Amplitude (% day 0)	EDL CAP Amplitude (% day 0)	FDP CAP Amplitude (% day 0)
NIH 15	175	123 %	160 %	66 %	11%

The second cat (NIH 16) was implanted with recording cuff electrodes on the distal Median and Superficial Radial nerves, as well as stimulating nerve cuff electrodes on the proximal branches of these same nerves. The proximal Median cuff was designed as a blocking cuff, with a reservoir to contain local anesthetic (Lidocaine) around the nerve and a catheter connecting to the backpack for access to the nerve (Hoffer and Loeb, 1983). The stimulating electrodes in the blocking cuff are used to evoke a compound signal in the distal recording cuff and monitor the level of block of the nerve during experiments.

Table 2 provides a summary of the status of the instrumented nerves in NIH 16 up to the end of November, 1995. Both instrumented nerves are healthy, with the Radial nerve showing a large increase in CAP amplitude from day 0.

Table 2: Status of subject NIH 16, Nov. 24, day 57

Subject	Total Days Implanted	Median CAP Amplitude (% day 0)	Radial CAP Amplitude (% day 0)
NIH 16	57	80 %	264 %

The two subjects from Year Three have been recorded from extensively during voluntary tasks with very good results, and future implants are being planned.

B. Simulation of Closed-Loop FES State Controller During Walking

State Controller

A simulation of a state controller approach to closed-loop FES was developed in Matlab and is presented in Fig. 1. The state controller used two neural signals (Median ENG and Radial ENG) as inputs to derive the timing of muscle activity for the Palmaris Longus. The neural signals were amplified, filtered, bin-integrated to 10 ms bins, smoothed, and normalized, and a single threshold was applied to each signal to produce a binary ENG signal. The transitions (low to high, or high to low) of the neural inputs were used to initiate changes in the output state of the controller. Note that the controller has two output states, high or low, which are intended to reflect phases of EMG activity in selected muscles. The controller output was used to determine when stimulation should be applied to paralyzed muscles to replicate natural patterns of muscle activity during walking.

During the off-line simulations, the actual PalL activity (binary signal produced with 10% threshold) was subtracted from the predicted PalL activity (binary signal) to produce an error signal. This error signal was used to set the parameters (i.e., ENG thresholds) to most closely predict the timing of the PalL activity (i.e., the timing of state transitions). The integrated absolute error signal divided by the length of the data sample gives an objective analysis of the percent accuracy of the prediction. Details of the state controller are provided in the attached paper in Appendix A.

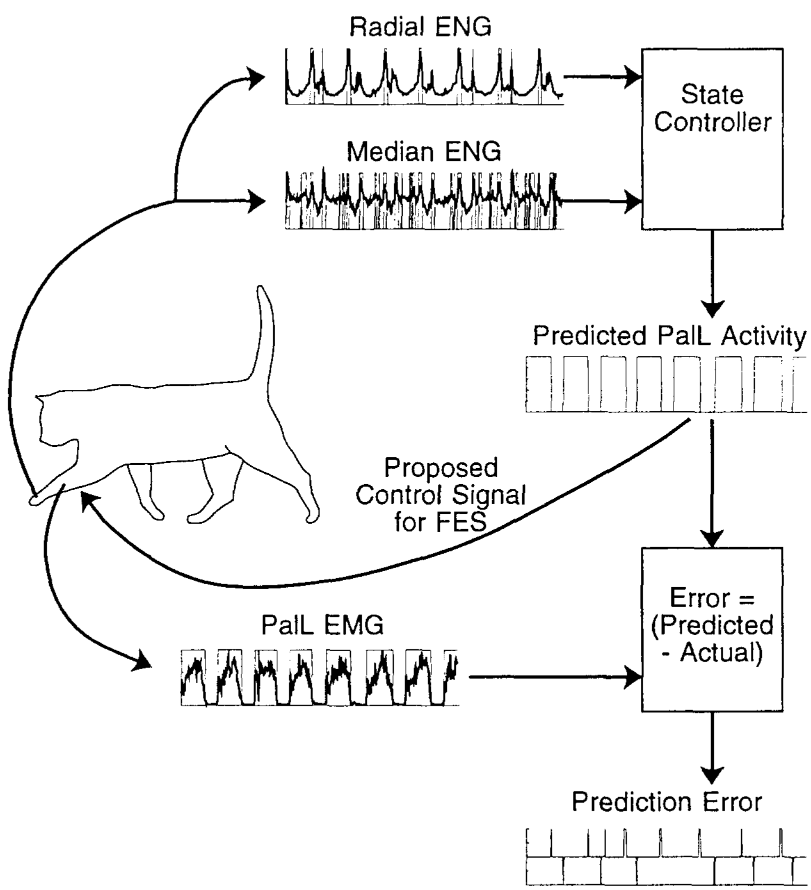


Figure 1: Schematic of simulation of closed-loop FES state controller

State Controller Simulation Results

The state controller was tested on data previously recorded from a number of different animals in a variety of different walking conditions (treadmill speeds and slopes). The accuracy and robustness of the controller with data from different conditions were examined, along with the effects of each of the parameters (ENG thresholds and state transition delay time - see attached paper). Figure 2 shows the results from one set of data in which the thresholds were both set at 0.6, or 60% of the peak ENG signal for the set of data. The predicted PalL activity (trace 4) is presented on top of the actual recorded EMG and the error signal (trace 5) shows small errors in the predicted signal (5.4%). The accuracy in the prediction was considerably greater for time of EMG onset than for the time of EMG termination.

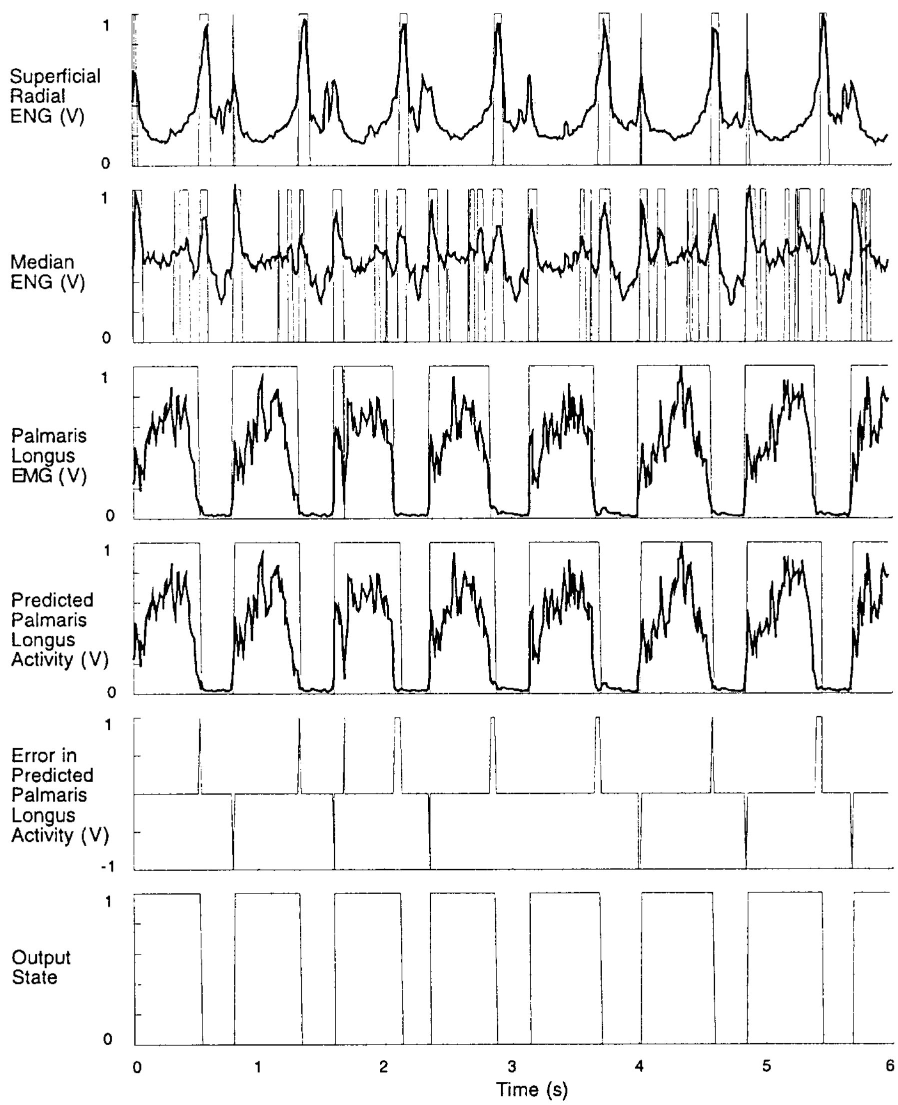


Figure 2: State controller output for data recorded from NIH 12 (day 85a, 0.5m/s, level). Error = 5.4%.

The state controller was then tested on data recorded during faster walking (in the same cat, same recording session) with the results shown in Fig. 3. The ENG thresholds were the same as for Fig. 2. The state controller correctly predicted every step although with somewhat larger overall error than for the previous set of data largely because greater errors occurred in the prediction of EMG onset.

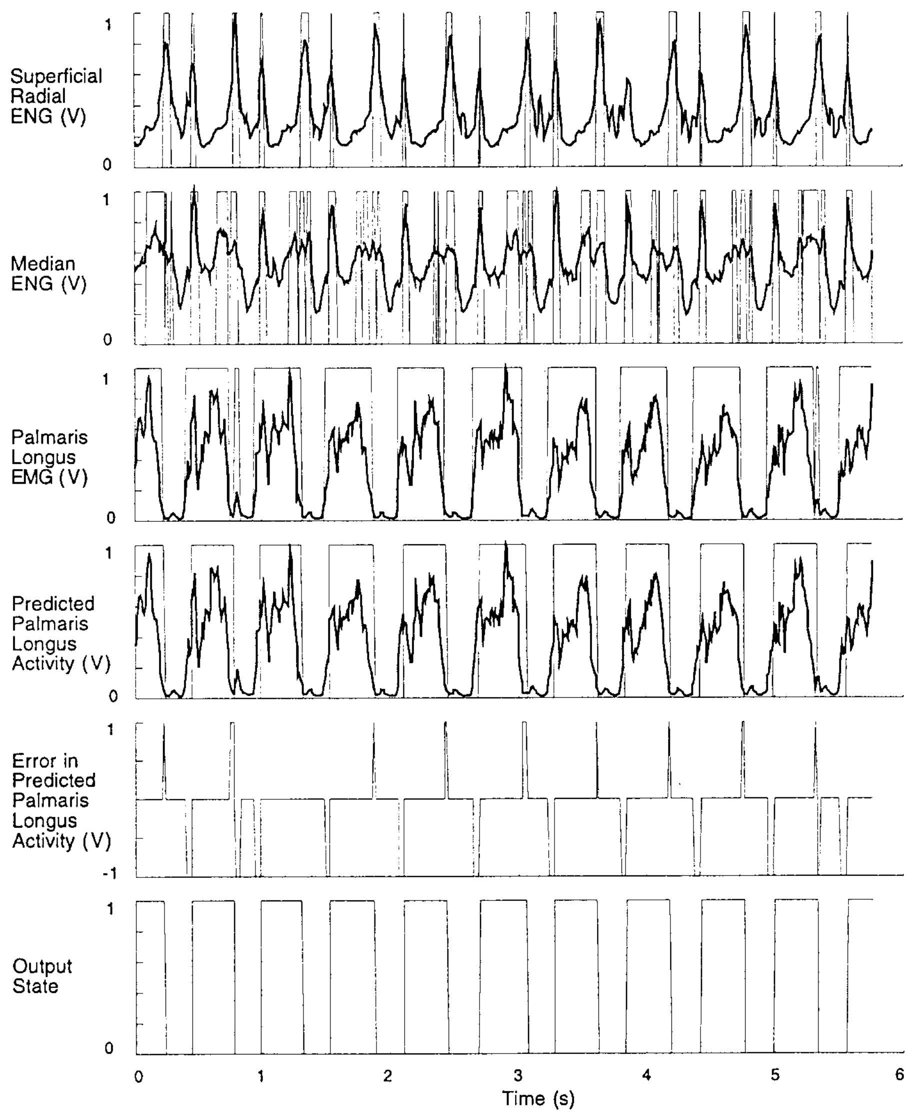


Figure 3: State controller output for data recorded from NIH 12 (day 85c, 1.0m/s, level). Error = 12.1%.

The results of testing the state controller on data collected from multiple subjects in a variety of walking conditions suggests that the method of implementing cutaneous neural signals for closed loop control of FES can be both reliable and robust. Tuning threshold parameters for particular data can reduce or minimize the prediction errors of the state controller. The results of testing showed that the state controller was largely insensitive to step variations and gait speed (0.5 - 1.0 m/s) even though the same set of thresholds was used for all conditions. This demonstrates that the natural modulations in the activity of cutaneous afferent nerves closely reflect transitional features in gait patterns and this property can be successfully used to predict the times of activation of muscles with high accuracy.

C. Implementation of Closed-Loop FES State Controller

Following simulations of closed-loop FES state controllers in a variety of walking conditions with different subjects, a real-time system was designed in hardware to process the neural signals and a digital controller to implement the state controller. The Median and Radial nerve signals were amplified and filtered (see earlier Progress Reports), and bin integrated to 10 ms bins with S/H circuitry. Schmidt triggers were used to threshold the neural signals and produce binary signals as inputs to the digital controller. The output of the state controller was used to drive a biphasic pulse generator and a constant current stimulator to stimulate the PalL muscle directly.

Initially, the controller was configured for an open-loop design where the stimulation control signals were generated but stimulation was not applied to the muscle. The timing of predicted muscle activity was compared in real time to the actual EMG recorded from the PalL as the cat walked on the treadmill.

The second set of experiments included stimulations superimposed onto the natural PalL EMG to verify that the timing was correct and that conditioning of the neural signals to omit stimulus artifacts did not introduce errors to the system. For these experiments, switching circuitry was used to ground the nerve cuff signals (after two amplification stages) prior to and following the stimulus pulse. Fig. 8 shows the results of stimulus artifact rejection during stimulation.

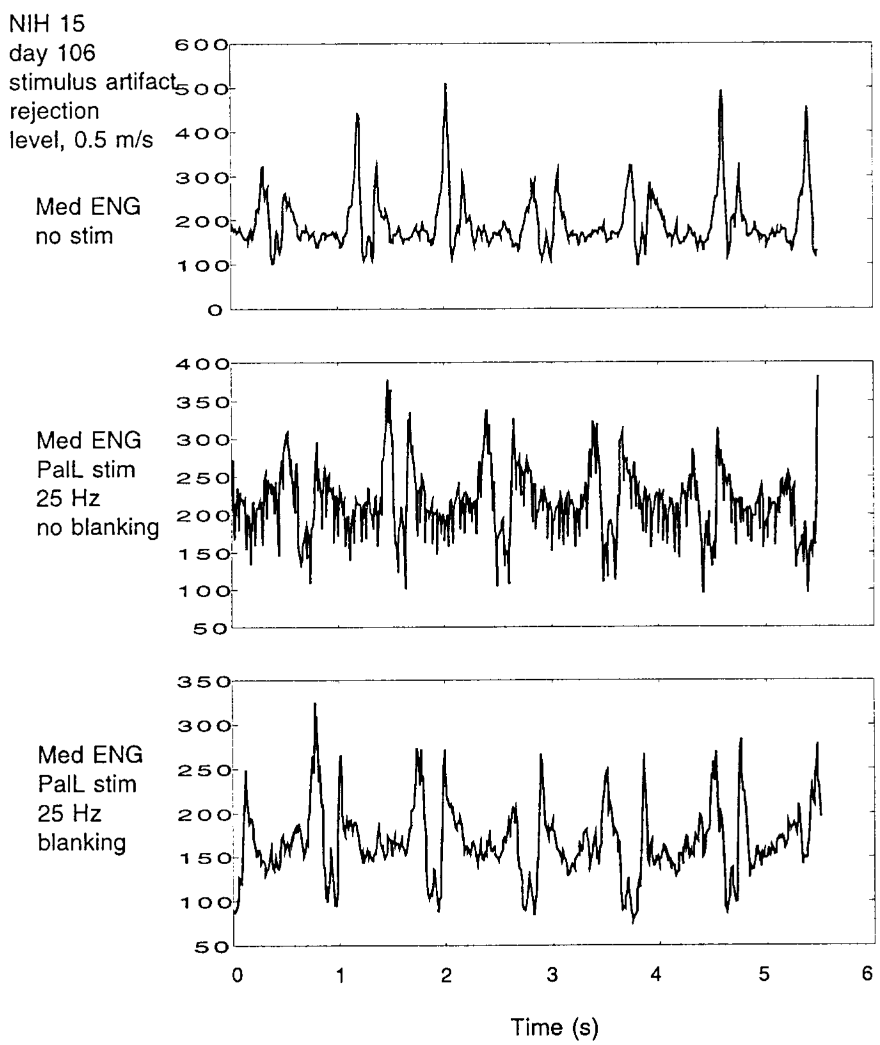


Fig. 8: Rectified, bin-integrated Median nerve ENG (μV) recorded during walking on the treadmill, with Palmaris Longus tonically stimulated at 25 Hz (data from NIH 15, day 106, level, 0.5 m/s)

The third set of experiments included blocking the motor innervation of the PalL (as well as several other wrist flexors) through the infusion of a local anesthetic into a blocking cuff around the proximal Median nerve. Once the proximal conduction block was in effect, the state controller was used to drive stimulation of the PalL and partially restore function to the paralyzed muscle and wrist joint during walking on the treadmill in a variety of conditions. The results (not shown here) were very positive and validated the computer simulations of the state controller.

D. Progress with Forelimb Task

An additional visiting graduate student joined the lab in Nov. 1995: Morten Hansen will study aspects of the forelimb task as his MScEE thesis project to be awarded by Aalborg University.

Functional Overview of Task

In the current paradigms of the forelimb reaching and grasping task, three types of trials are being studied: normal, stiffness perturbation, and slip trials.

a) normal trials: the joystick behaves like a ordinary spring in one direction (Y);

b) stiffness perturbation trials: at unexpected times and positions, the virtual spring coefficient (in direction Y) can be made to change suddenly;

c) slip trials: at unexpected times and positions, tangential displacements can be generated suddenly in direction X, producing a slip.

Hardware

Figure 4 shows the forelimb task setup, with motor and joystick orientation. When the lever is moved in the virtual spring direction (Y direction is towards cat), the force resistance is controlled by a computer in a closed loop system. A second, slip inducing motor moves the lever in a perpendicular plane (X direction). This second motor is normally locked in position, so only movement in the Y direction is possible. The force resistance is controlled by setting the Y motor (motor B in Fig. 4) supply current proportional to the lever angle (see Fig. 5), which is used as feedback in the closed control loop, and is measured using the potentiometer setup. This way, the virtual spring resistance is configured to be proportional to the lever angle, thereby simulating the features of a mechanical spring. The stiffness coefficient is adjustable. When the lever is pulled to the specified target position in front of the mouth of the cat, a food reward is supplied. After a specified feeding time, the lever is returned to the origin by increasing the stiffness, which results in the lever being pulled away from the subject.

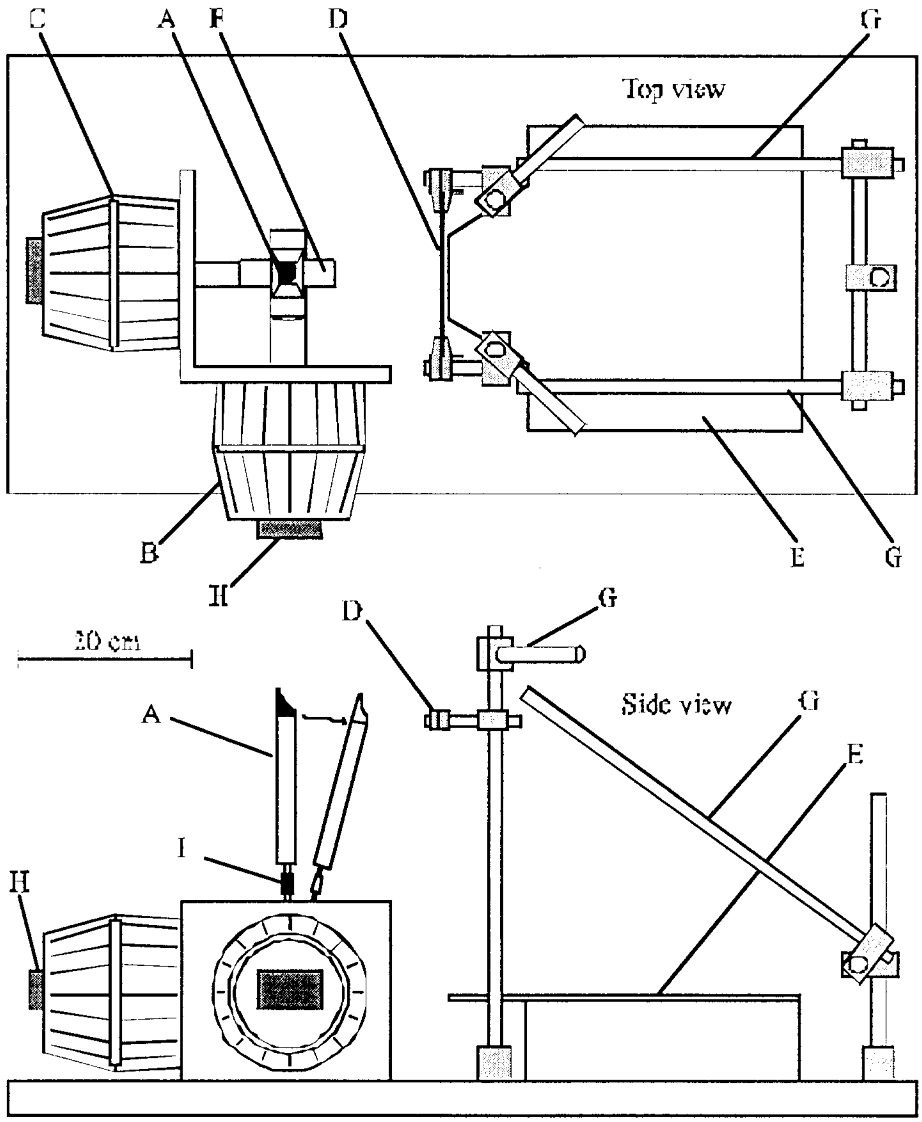


Figure 4: Joystick hardware illustrated in top view (top) and side view (bottom). A: lever with food reward hose in it, B: Motor for virtual spring force resistance, C: Motor for inducing slip, D: barrier to keep the subject from moving forward, E: subject platform, F: bearings system, described by Bernard Dov Adelstein at MIT, G: frame for jacket mounting, used to secure subject on platform, H: position sensor system, I: strain gauges.

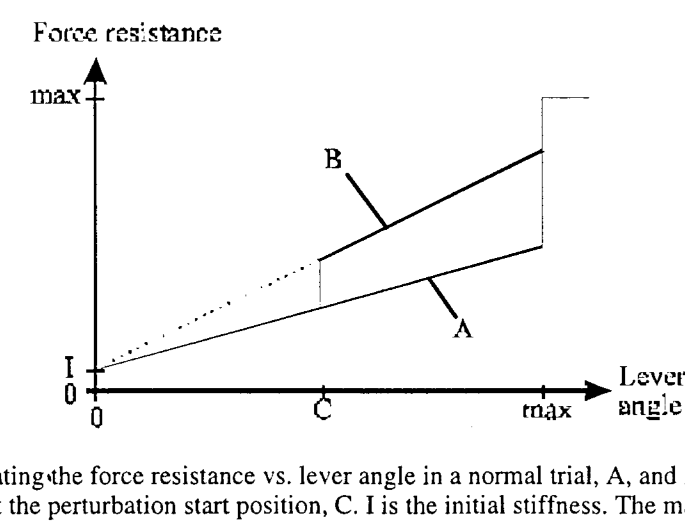


Figure 6: Graph illustrating the force resistance vs. lever angle in a normal trial, A, and in a perturbed trial, B. The perturbation is evoked at the perturbation start position, C. I is the initial stiffness. The maximum values indicate the motors' maximum force, and the predefined outermost position of the lever.

In the slip movement dimension (X), a computer controls the position of the lever. The lever position is kept the same until a slip movement is required. The slip movement is a sudden tangential movement with specified amplitude, direction, and speed at a specified time or position. After the slip movement, the lever position is kept in a path which connects the current lever position point and the targeted end position in the shortest distance, or a path which connects the current lever position point and the origin in case the subject lets go of the lever, as illustrated in Fig. 6.

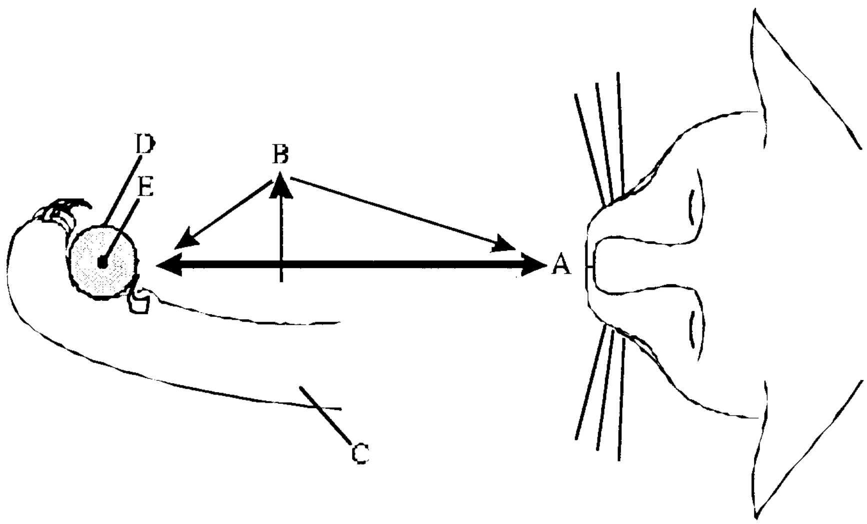


Figure 6: Top view of the movement directions and grasp. A: virtual spring movement directions, B: slip movement direction, C: subject's left forelimb, D: lever positioned at the origin. E: Food reward nipple. As the arrows indicate, the lever will return to its origin at any time, if the subject lets go. After a slip movement, the lever will travel in the path that leads directly towards the subject, or towards the origin of the lever.

Preliminary Forelimb Task Data

Figure 7 shows preliminary data recorded from the cat forelimb during the forelimb reaching and grasping task. The data has been recorded at the end of the grasping phase, as the stiffness increased and the joystick returned to the zero position (final trace). The Median and Radial nerves (traces 1 and 2) showed increased activity as the stiffness increased and the force applied to the joystick by the cat increased (trace 7). The four forelimb muscles (traces 5 - 8) showed a range of individual responses to the increase in stiffness and the change in position.

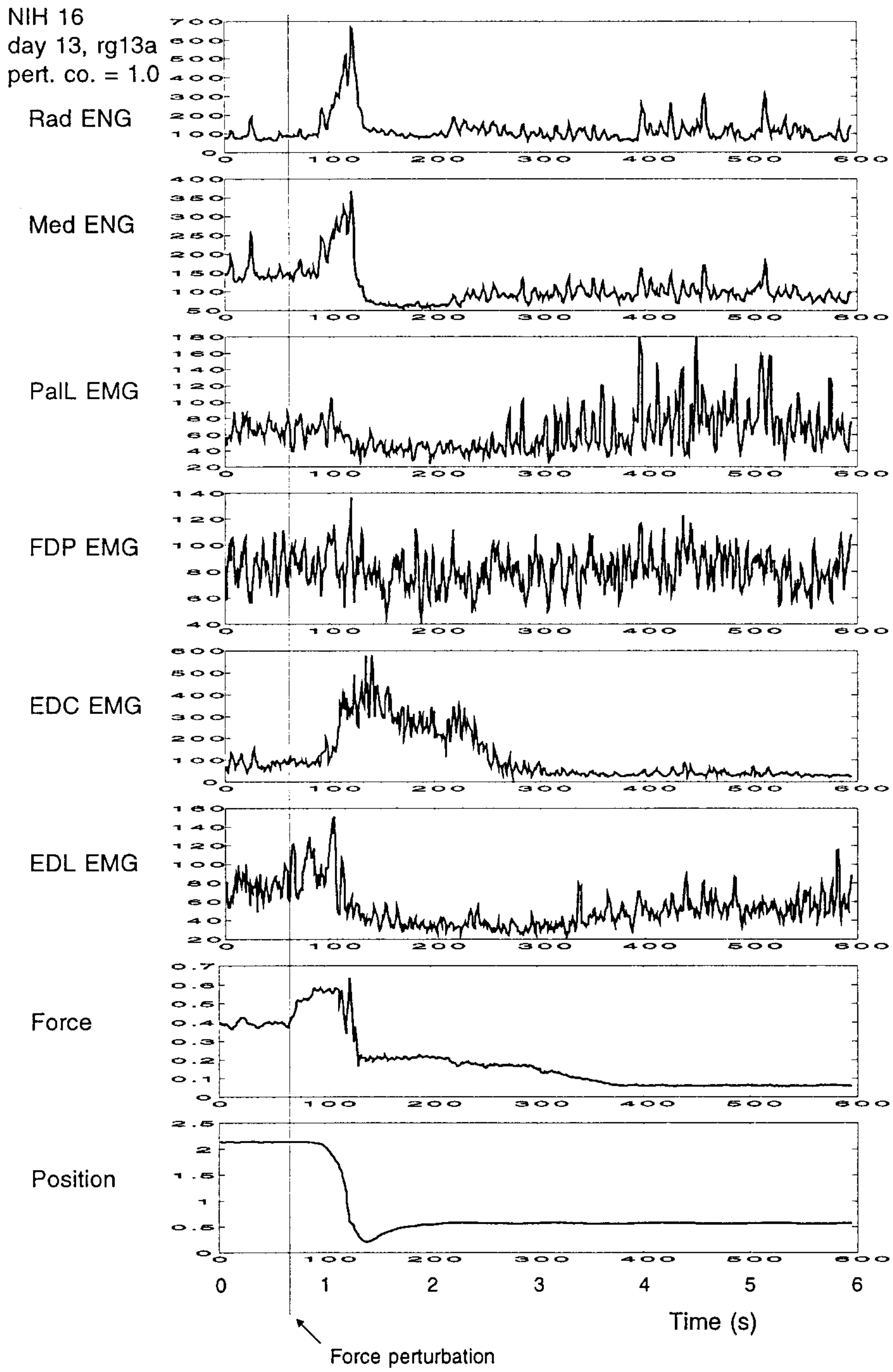


Figure 7: Preliminary forelimb task data, showing ENG and EMG responses to force perturbation (data from NIH 16, day 13)

E. Publications and Meetings

Publications

In the twelfth quarter, K. Strange and J.A. Hoffer published a paper entitled "Using Cutaneous Neural Signals to Predict Cat Forelimb Muscle Activity During Walking" in the proceedings of the IEEE Systems, Man, and Cybernetics meeting held in Vancouver, B.C., Oct. 1995. A copy of the paper is in Appendix A.

Also during the twelfth quarter, the investigators continued to develop three manuscripts for peer-reviewed journals based on results obtained from the current NIH contract. The third manuscript is being developed from collaborative work with Drs. A. Kostov and R.B. Stein at the University of Alberta. The three manuscripts are outlined in Progress Report #11.

Meetings

In Oct. 1995, Andy Hoffer and Kevin Strange attended the 26th Annual NIH-NINDS Meeting in Bethesda, MA, where they reported on the previous years' results and future directions.

In Oct. 1995, Kevin Strange presented a paper at the IEEE Systems, Man, and Cybernetics meeting in Vancouver, B.C.

In Nov. 1995, Kevin Strange and Andy Hoffer attended the Neuroscience meeting in San Diego, CA, where they presented a poster detailing simulations of a closed-loop state controller for FES applications.

V. Plans for Thirteenth Quarter

In the thirteenth quarter we intend to:

1. continue to examine histopathologically the nerves from Year One and Year Two cats (objective 5)

2. continue Year Three series of implants, implanting cuffs appropriate for smaller proprioceptive nerves (objective 3)

3. complete the construction of an 8-channel stimulator to be used for FES of forelimb muscles (objective 4b)

4. complete the construction of hardware and the software design for controlling the reaching task (objective 4a,b)

5. continue to investigate real-time state controller approaches for closed loop control of FES during walking utilizing neural feedback (objective 4)

6. analyze walking data with our collaborators (objective 7)

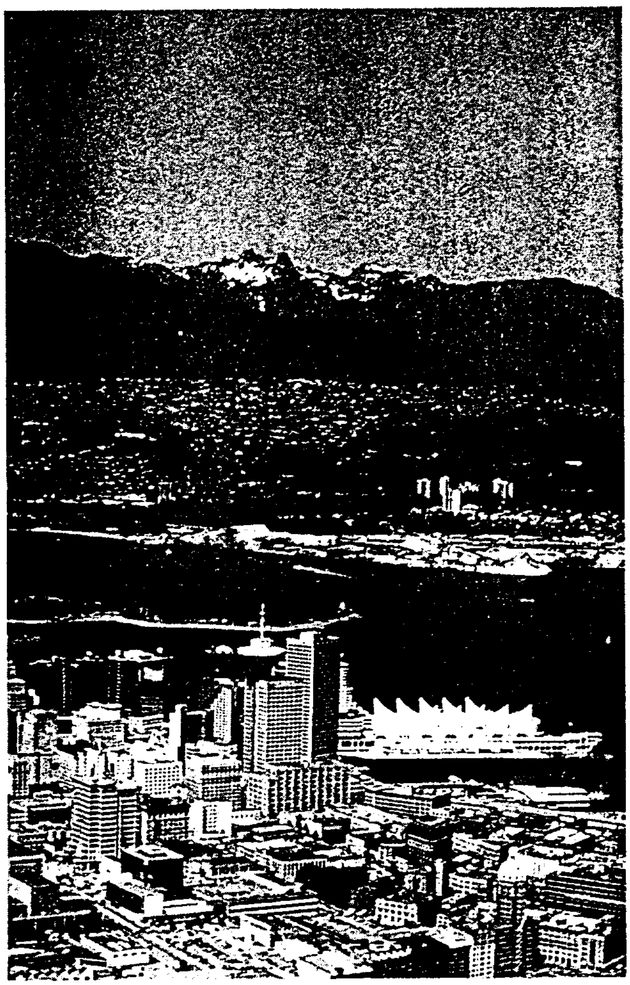
V. Reference

Hoffer, J.A. and Loeb, G.E. A technique for reversible fusimotor blockade during chronic recording from spindle afferents in walking cats. **Exp. Brain Res. Suppl. 7**:272-279, 1983.

VI. Appendix A

Paper published in Proc. IEEE SMC, Vol. 2, pp. 1199-1204, Oct. 1995, Vancouver, B.C., CANADA

1995 IEEE International Conference on Systems, Man and Cybernetics



Intelligent Systems for the 21st Century

Vancouver, British Columbia Canada

October 22 - 25, 1995

Volume 2 of 5
95CH3576-7

IEEE Systems, Man and Cybernetics Society

USING CUTANEOUS NEURAL SIGNALS TO PREDICT CAT FORELIMB MUSCLE ACTIVITY DURING WALKING

Kevin D. Strange and J. Andy Hoffer
Schools of Engineering Science and Kinesiology
Simon Fraser University, Burnaby, B.C., V5A 1S6, Canada

1. INTRODUCTION

In this study, our overall objective is to identify reliable sources of neural control signals and extract features, such as ground contact and slip information, that may be applied in closed-loop FES systems for restoring voluntary use of paralyzed muscles in humans. We present a method of recording cutaneous nerve activity in unrestrained cats walking on a treadmill, and using the electroneurograms (ENGs) to predict the timing of electromyograms (EMGs) recorded simultaneously in various muscles.

2. BACKGROUND

A closed-loop control system is preferred for providing more efficient and useful function to paralyzed muscles and extremities with functional electrical stimulation (FES). An attractive approach under study is to utilize the natural sensors that remain available in the extremities to derive contact, force, and position information from peripheral nerve recordings [1,2,3]. In a recent clinical trial to correct for drop-foot in a stroke patient, a closed-loop FES system implemented the use of cutaneous activity recorded from the Sural nerve as feedback [4].

3. METHODS

Data for these experiments were obtained from recording nerve cuffs implanted in the left forelimb of six cats, in which two of the Ulnar, Median, and/or Superficial Radial nerves were instrumented below the elbow. The distal location of the nerve cuffs ensured that the recorded ENGs were largely cutaneous sensory in nature and contained minimal motor content. Figures 1 and 2 show medial and lateral views of the left forelimb of the cat with recording cuffs on the Median and Radial nerves respectively.

Intramuscular EMG electrodes were implanted in two wrist flexors, the Palmaris Longus and the Flexor Carpi Ulnaris, and two wrist extensors, the Extensor Carpi Ulnaris and the Abductor Pollicis Longus. An implanted thermistor recorded local limb temperature. All device leadout wires were routed to a common percutaneous exit point and attached to a specially designed backpack containing a printed circuit board and a 40-pin connector. All surgical and experimental protocols were in accordance with guidelines set by the Canadian Council of Animal Care and were approved by the University Animal Ethics Committee.

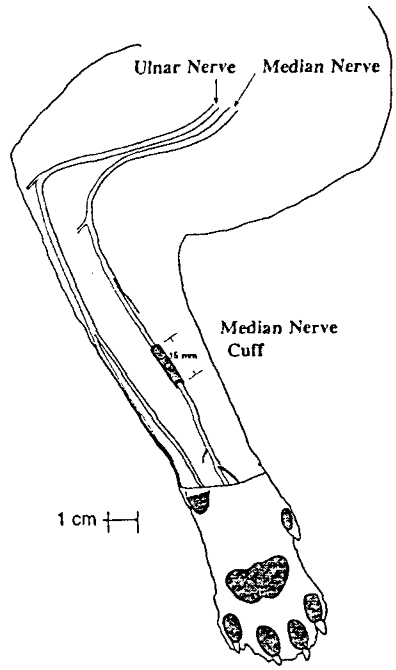


Figure 1: Medial view of the cat left forelimb with recording cuff on the Median nerve

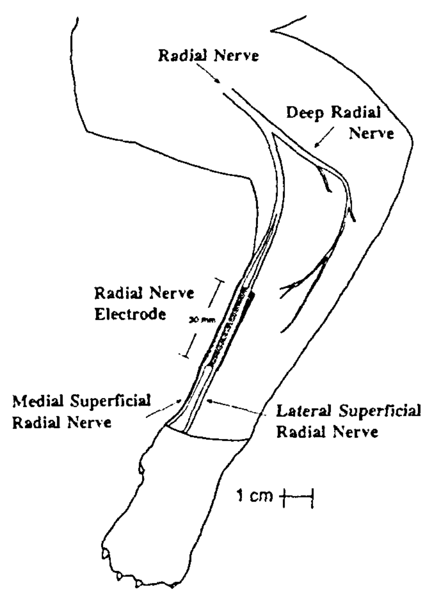


Figure 2: Lateral view of the cat left forelimb with recording electrodes on the Radial nerve

0-7803-2559-1/95 $4.00 © 1995 IEEE

The cat was connected via a ribbon cable to the recording setup and data were recorded while the cat walked on a powered treadmill. Signals from the nerve cuffs were processed on-line by amplifying (typically x100,000) and high-pass filtering (1 kHz) to remove contamination from EMG activity generated by nearby muscles. EMG contamination of nerve cuff signals was monitored during recording by examining the power spectrum of the nerve cuff signals and listening to the signals through a loudspeaker. The EMG signals recorded from the four implanted muscles were amplified (typically x1000) and bandpass filtered (50 Hz - 1 kHz). All physiological signals were recorded on a 20 channel, 10 kHz/channel FM tape recorder. We simultaneously videotaped the cat walking on the treadmill to correlate the physiological signals with events in the gait cycle such as paw contact and lift-off.

The timing of the EMG bursts from the four instrumented muscles was compared to data for cat forelimb muscles during walking available from the literature [5,6]. We confirmed that the flexors, PalL and FCU, exhibited strong, modulated signals corresponding closely to the stance phase of the forelimb. The extensors that we monitored showed low levels of activity and were not nearly as modulated with gait as the flexors. EMG amplitude modulation features from forelimb muscles during walking have not been well-reported in the literature.

Off-line processing consisted of sampling the ENG (10 kHz) and EMG (1kHz) signals and importing the data into Matlab. The digital signals were then rectified, bin-integrated to bin widths of 10 ms, smoothed with a 3-point, balanced filter, and normalized to reduce the amount of data and produce relatively clean waveforms for analysis. Figure 3 presents processed ENG data from the Radial and Median nerves and EMG data from the PalL and FCU muscles recorded from during walking on the treadmill. All four signals show clear modulations with the gait cycle, although none of the signals are directly correlated with the others (highest absolute correlation coefficient is r=0.57 between PalL and FCU).

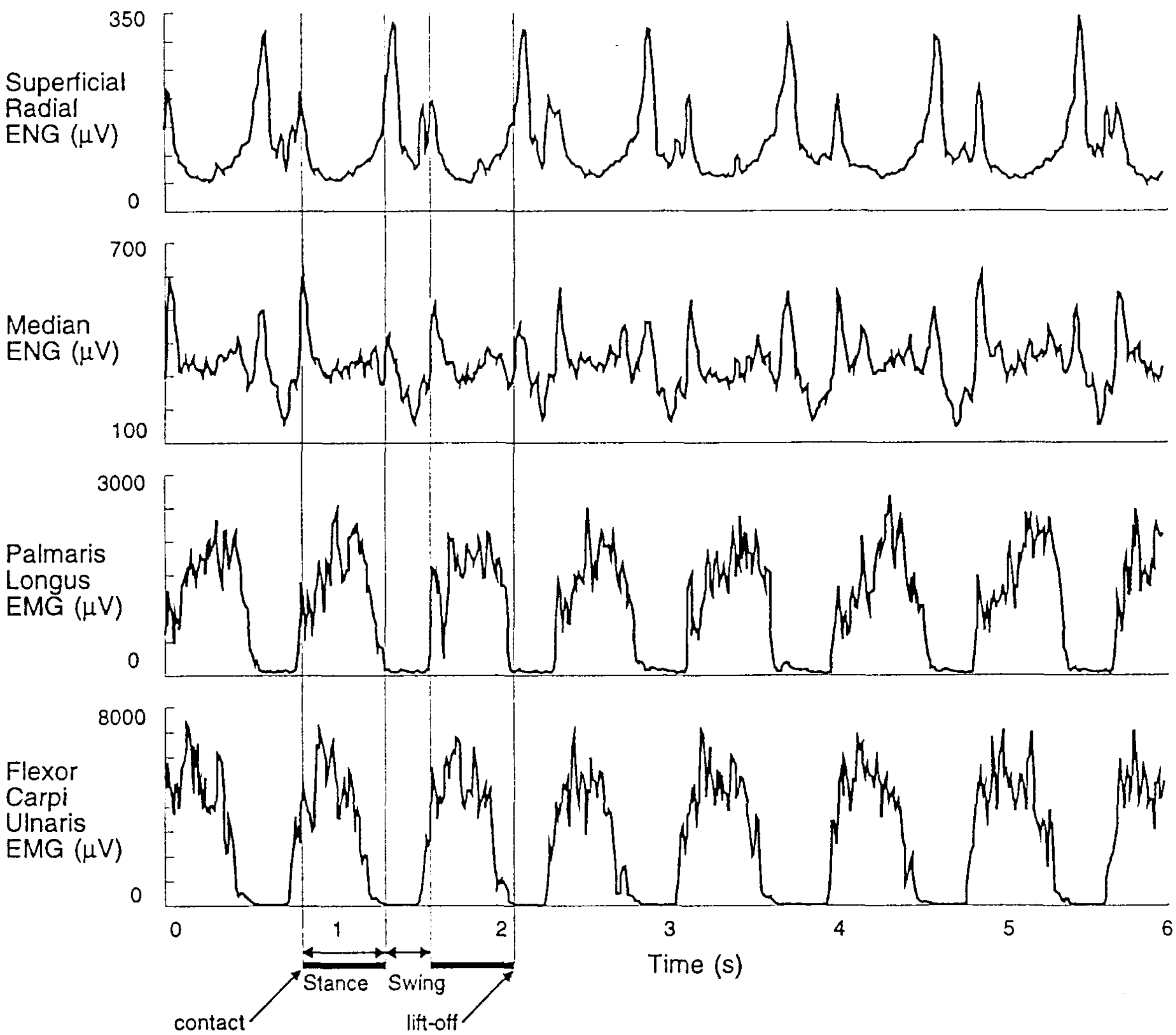


Figure 3: Processed ENG and EMG signals recorded in the cat forelimb during walking. Data from NIH 12, day 85, 0.5 m/s, level treadmill.

Two state machine controllers were designed using the cutaneous signals as inputs to predict the timing of simultaneously recorded muscle activity signals. Thresholds for ENG (typically 40-70% of normalized signal peak) and EMG (typically 5-10% to detect presence or absence of muscle activity) were selected to identify discrete events and phases in the physiological signals and convert these signals to binary form. A two-state machine was developed to predict the timing of PalL activity, and a four-state machine was developed to predict the timing of both PalL and FCU muscle activity. Each state controller was evaluated in terms of the output state error between the predicted muscle timing and the actual muscle activity for the test data.

4. PREDICTION OF THE TIMING OF ACTIVITY OF ONE MUSCLE

A two-state controller was designed to predict the timing of PalL activity using the current state of the controller and the two binary ENG signals as inputs, and specifically detected the large spike of Median activity related to paw contact and the beginning of stance phase (shown by heavy bars on the time scale of Figs. 3 and 4) and the large spike of Radial activity generally related to lift-off and the initiation of swing phase. The controller implemented a delay counter at state transitions to avoid noisy transition periods between states due to multiple threshold crossings. Table 1 summarizes the state controller.

Table 1: Two-state controller to predict timing of PalL.

Current State	Predicted PalL Activity	Next State	Transition to Next State Input
0	PalL off	1	Median ENG spike at contact thresh = 0.7
1	PalL on	0	Radial ENG spike at lift-off thresh = 0.4

Figure 4 shows processed nerve (top trace, Superficial Radial; second trace, Median) and muscle (third trace, PalL) signals with their corresponding binary levels of activity based on arbitrary thresholds (0.4, 0.7, 0.1 respectively), along with the binary output of the state-machine controller (fourth trace, predicted PalL activity), the error of the state machine output (fifth trace, equal to panel 3 minus panel 4), and the output state of the controller (bottom trace). The state controller implemented two states, representing a stimulation phase and a quiet phase, and the output closely predicted the recorded timing of PalL activity, with a cumulative state error of 4.2% for the test data.

5. PREDICTION OF THE TIMING OF ACTIVITY OF TWO MUSCLES

The PalL and FCU traces in Fig. 3 clearly show that the FCU activity starts prior to paw contact and prior to the beginning of PalL activity, and concludes prior to paw lift-off. The state error of applying the output of the two-state controller tuned to predict PalL activity to the FCU was unacceptably high at 16.6%. To accurately predict both PalL and FCU activity, a four-state controller was necessary. The Median ENG spike at paw contact and the radial ENG spike at paw contact provided the transition inputs to the state machine, and two sets of ENG thresholds were implemented to detect the differences in muscle activity timing. Table 2 summarizes the state controller.

Table 2: Four-state controller to predict timing of both PalL and FCU activity.

Current State	Predicted PalL Activity	Next State	Transition to Next State Input
1	PalL off FCU off	2	Median ENG spike at contact thresh = 0.35
2	PalL off FCU on	3	Median ENG spike at contact thresh = 0.7
3	PalL on FCU on	4	Radial ENG spike at lift-off thresh = 0.5
4	PalL on FCU off	1	Radial ENG spike at lift-off thresh = 0.4

Figure 5 shows the output of the four-state controller when tested on the original ENG and EMG data, with predictions for both PalL (top trace, original PalL activity; second trace, predicted PalL activity; third trace, error in predicted PalL output) and FCU (fourth trace, original FCU activity; fifth trace, predicted FCU activity; sixth trace, error in predicted FCU output). The output state errors for the timing of PalL and FCU activity were 4.0% and 7.4% respectively, which showed that independently controlling each muscle by implementing four states (bottom trace) could reduce the overall error for both outputs.

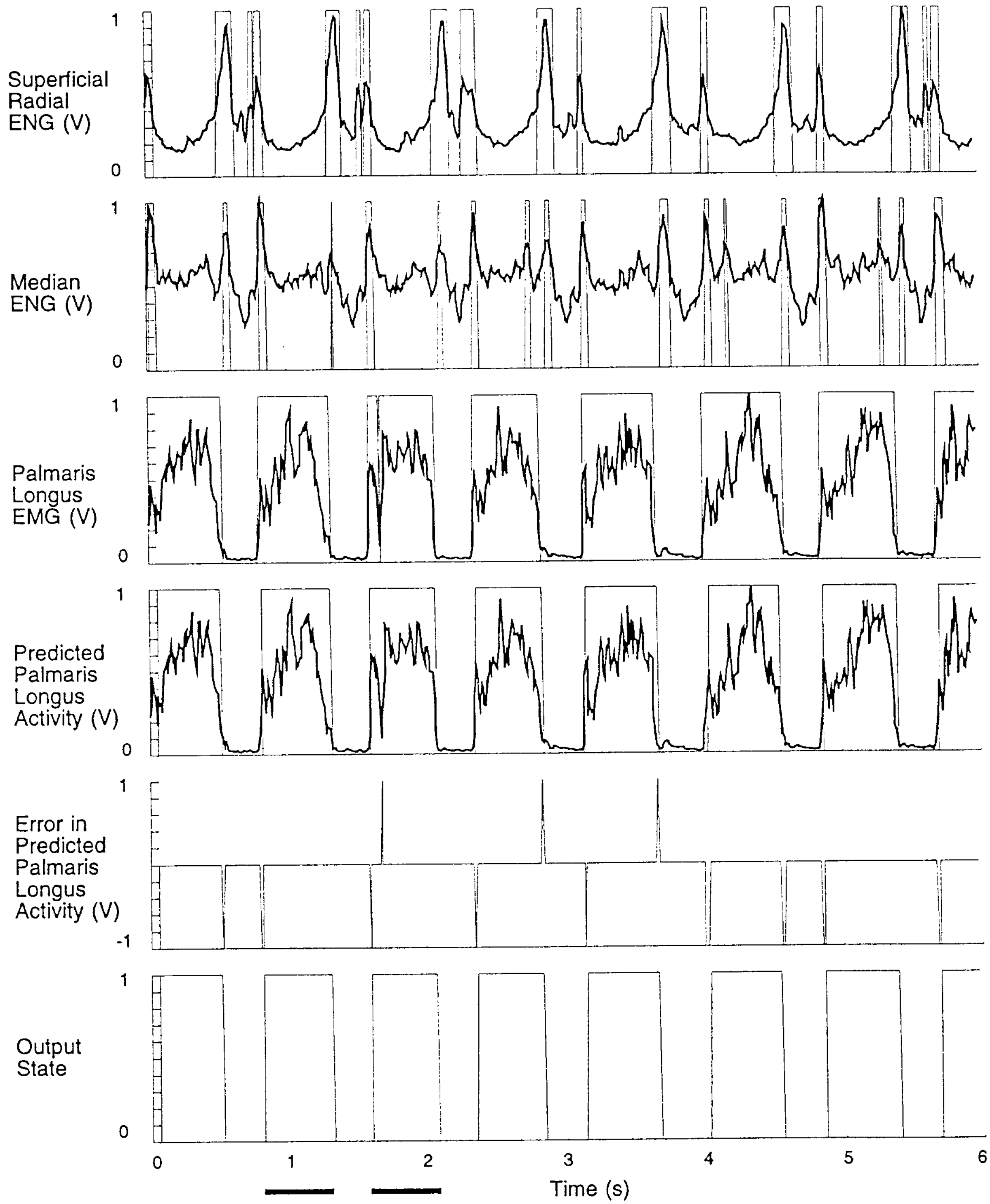


Figure 4: Two-state controller output that predicts timing of PalL activity.

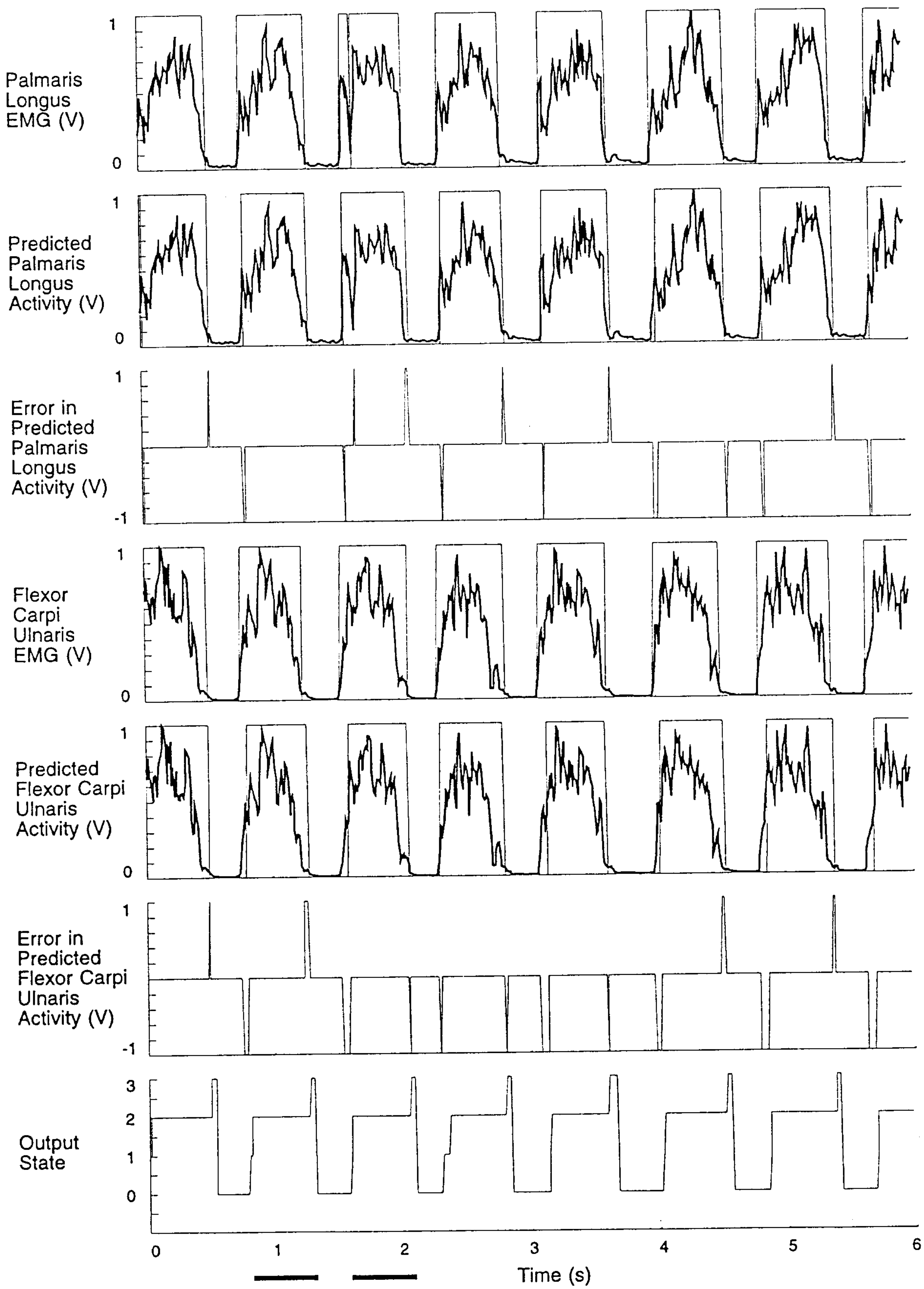


Figure 5: Four-state controller output that predicts timing of PalL and FCU activity.

6. DISCUSSION

Two-state and four-state controllers were designed which utilized two cutaneous ENG signals as inputs to determine state changes and accurately predict the timing of activation of a single muscle or two independent muscles. The controllers specifically detected neural events related to paw contact at the beginning of stand and to paw lift-off at the beginning of swing. The controller output was rate-independent (unlike previous closed-loop FES systems that utilized counters to determine the period of certain states, such as swing [4]).

These state controllers have been specifically tuned using hand-crafted rules on test data as a demonstration of the potential use of cutaneous feedback in closed-loop control of FES. The limitations of applying the same controller with the same threshold values for the input signals to a variety of conditions (velocities, slopes, changes in neural signals over time) must be recognized. Tuning simple controllers to minimize the error on one set of test data will usually create a tradeoff in generalization error with new sets of inputs and different conditions, although restricting the conditions or environment that a FES system operates in can make the state controller approach a viable one.

Although the present approach is limited to predicting the timing of muscle activations, more complex controllers involving machine learning techniques and pattern recognition that are being developed can theoretically accommodate a wider range of input conditions (such as rate and slope changes, muscle fatigue, and spasticity), and can accurately predict both the timing and continuously varying levels of muscle activity [7,8]. Using these approaches, FES controllers implementing neural feedback should result in clinical applications of FES with increased accuracy and robustness, and increased functionality of paralyzed limbs.

7. REFERENCES

[1] Hoffer, J.A. Closed-loop, implanted-sensor, functional electrical stimulation system for partial restoration of motor functions. U.S. Patent No. 4,750,499.

[2] Hoffer, J.A., and Haugland, M. Signals from tactile sensors in glabrous skin suitable for restoring motor functions in paralyzed humans. in *Neural Prostheses: Replacing Motor Function after Disease or Disability*, R.B. Stein, P.H. Peckham, and D. Popovic, editors. Oxford Univ. Press, pp. 99-125, 1992.

[3] Haugland, M.K. and Hoffer, J.A., Slip information provided by nerve cuff signals: application in closed-loop control of functional electrical stimulation. *IEEE Trans. Rehab. Eng.*, Vol. 2, pp. 29-36, March 1994.

[4] Sinkjær, T., Haugland, M., and Haase, J. The use of natural sensory nerve signals as an advanced heel-switch in drop-foot patients. in *Proc. of the 4th Vienna Workshop on FES*, pp. 134-137, 1992.

[5] English, A. An electromyographic analysis of forelimb muscles during overground stepping in the cat. *J Exp. Biol.*, Vol. 76, pp. 105-122, 1976.

[6] Hoffman, P., Illert, M., and Wiedemann, E. EMG recordings from the cat forelimb during unrestrained locomotion. *Neuro Lett.*, S22:S126, 1985.

[7] Popovic, D.B., Stein, R.B., Jovanovic, K.L., Dai, R., Kostov, A., and Armstrong, W.W. Sensory nerve recording for closed-loop control to restore motor functions. *IEEE Trans. Bio. Eng.*, Vol. 40, pp. 1024-1031, Oct. 1993.

[8] Kostov, A., Stein, R.B., Popovic, D., and Armstrong, W.W., Improved methods for control of FES for locomotion. in *Proc. of Modeling and Control in Biomedical Systems*, Galveston, pp. 422-427, Mar. 1994.

ACKNOWLEDGEMENTS

We thank Y. Chen, P. Christensen, D. Crouch, K. Kallesoe, C. Kendall, S. Schindler, and D. Viberg for technical support.

Funding for this research was provided by the National Institutes of Health Neural Prostheses Program (contract number NIH-NINDS-NO1-NS-3-2380, J.A. Hoffer, P.I.).